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MODELOCKING AND WAVEGUIDE AMPLIFIERS USING Cr:FORSTERITE AND Cr:YAG

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13. ABSTRACT (Maximum 200 words)

Solid state laser systems have been demonstrated using Cr:YAG crystals. CW, regenerative modelocking and self-modelocking have been achieved with pulses as short as 120 femtoseconds being transform limited. Thin film amplifiers based on Cr:Forsterite on glass using a sol-gel deposition technique were fabricated and tested. Other techniques such as nanocrystal imbedded in an index matching matrix made of polymers were explored.

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The project was conceived at Cornell University by Dr. Clifford Pollock. The major accomplishments of this report were conducted in Dr. Pollock's laboratories at Cornell University. Similar systems were designed and fabricated at Rome Laboratory with support provided by Dr. Pollock. Steven Johns, Michael Hayduk, Douglas Norton, Mark Krol and Reinhard Erdmann were the Rome Laboratory personnel involved with this project.

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Final Report

Contract F30602-93-C-0003

Modelocking and Waveguide Amplifiers Using Cr:Forsterite and Cr:YAG

1 Introduction

We began this effort interactively designing suitable laser cavities for the Cr:forsterite and Cr:YAG lasers crystals that we had obtained and those that our coworkers at Rome Labs had received. We also began a systematic study of the thin-film growth of these materials for use as amplifiers. Our work supported the efforts at Rome Labs to generate modelocked laser pulses in the 1.3 and 1.5 μm regions using these new laser materials. Members from both labs spent time at the othet institution during this program, interacting with eaqch other, and sharing knowledge and experience. When completed, we were able to generate femtosecond pulses from both the Cr:forsterite and Cr:YAG lasers in a reproducible and sustained fashion. This work represents the best mode locking results ever obtained from these laser systems to date.

2 Laser Research

A schematic of a typical laser cavity is shown below in Figure 1. The crystal (Cr:forsterite or Cr:YAG) is located at the focus of a z-folded optical resonator. The optocal cavity design is relatively straightforward. We found the critical aspects of the laser to be the temperature control of the crystal, and the optical system used to couple the pump beam into the laser crystal. The crystal in all systems we worked with was mounted on a thermoelectric cooler so that the temperature could be actively maintained below room temperature. We found performance improved with both host materials (forsterite and YAG) as the temperature decreased, but that below about 3 C the optical surfaces became fogged with condensed water from the air.

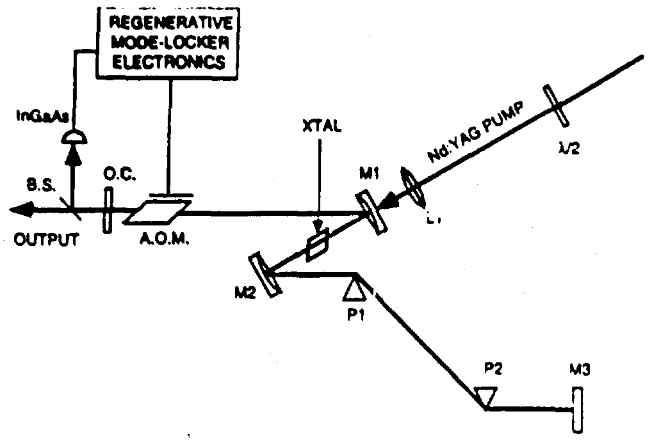

Figure 1: Schematic of the modelocked solid state laser.

We compromised between cooling the crystal for better power and yet not fogging the crystal surface by operating with crystal temperatures in the 10-15 °C range.

The focusing optics that directed the Nd:YAG pump beam into the crystal were found to be critical. For the Cr:forsterite work we used a single lens with focal length 10 cm, as shown in Figure 1. We were able to achieve excellent output power, and after considerable effort we were able to modelock this laser using a regenerative modelocking technique. However, we were unable to observe self-modelocking of the Cr:forsterite system. After interaction with Rome Labs concerning the choice of the optimal lens for pumping the laser, we did some careful calculations on our specific cavity. A plot of the mode profile in the crystal for our cavity is shown in Figure 2. It is quite clear that the mode overlap is not optimum. We feel that this is the reason why this laser would not self-modelock. The Kerr-lens self-focussing that drives the self-modelocking does not create enough gain discrimination in this pump configuration to initiate the modelocking.

Based on these calculations, several laser cavities were designed and built at Rome Labs. We had one interesting episode where the Rome Labs Cr:forsterite laser began to spontaneously pulse when aligned in a specific manner. After spending two days in the lab, we concluded that the gain medium was acting like a saturable absorber to the pump laser, causing the pump laser to break into spontaneous Q-switched operation. While this effect was interesting, we felt it was not quite useful enough to warrant a full

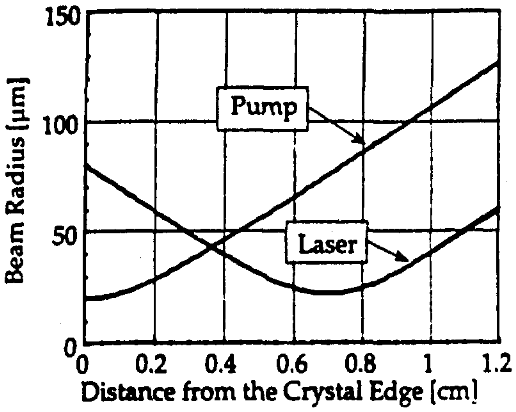

Figure 2: The calculated pump and laser beam radii as a function of distance from the edge of the Cr:forsterite cystal..

publication in a scientific journal.

By the time we discovered the poor mode overlap between the laser mode and pump beam, we had already begun extensive work on the Cr:YAG laser. Running the laser without any tuning element, it operated at 1.45 μm. The cavity design was similar to that shown in Figure 1, with the exception that Cr:YAG was now used as the gain crystal instead of Cr:forsterite. We first investigated it's cw characterisitics, and determined the optimum output coupler. The Cr:YAG laser has very low gain compared to the Cr:forsterite laser. A plot of the optimum output coupling is shown in Figure 3. The optimal coupling depends slightly on temperature, but effectively the best coupling for maximum power output was 2%. Such low output coupling indicates that Cr:YAG has very little gain. This fact came back to haunt us during the modelocking experiments.

We measured the tuning range of the laser using a variety of tuning elements. The data is shown in Figure 4. Fused silica gave the best output power, but completely cutoff lasing below 1.4 μm. This is attributed to the presence of OH^- in the glass material, which creates strong absorptions in the 1.4 μm region. Because the gain of the Cr:YAG laser is so low, it does not take very much additional loss to completely extinguish the laser output. A more dispersive prism, made from SF-14, was also tried. SF-14 introduced an overall loss, so the output power was reduced at all wavelengths, and it also had a small OH^- absorption feature, which is apparent from the tuning

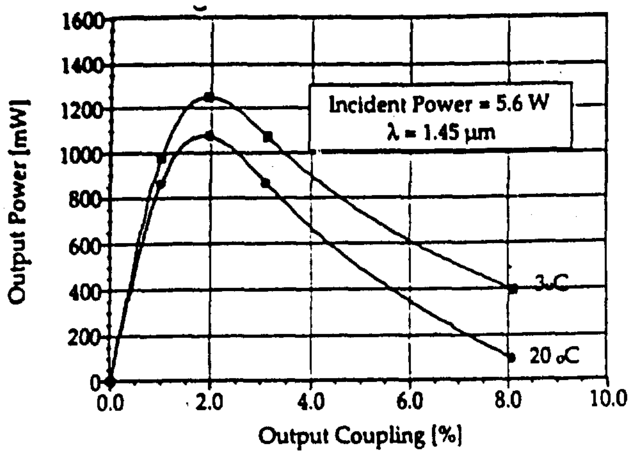

Figure 3: The variation of output power as a function of the output coupling for a fixed pump power of 5.6 W at 1.45 μm in Cr:YAG.

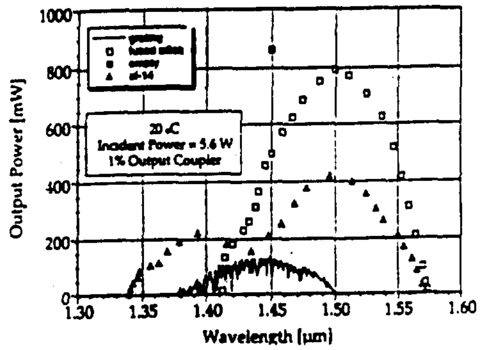

Figure 4: The variation in output power as a function of wavelength for several tuning elements in the Cr:YAG laser.

data in Figure 4. The output power of the laser was reduced by over 60% by the inclusion of the SF-14 prism in the cavity. Finally, we tried using a low loss grating as a tuning element. While the grating had a rated loss of 1% due to non-Littrow reflection, we observed a loss closer to 4% from the device. As a result, the output power and tuning range were dramatically reduced. The high dispersion of the grating allowed strong wavelength control of the laser. As the grating angle was adjusted the laser output power showed strong fluctuations. These power dips were correlated to atmospheric water absorption, coinciding with the OH^- absorption of water vapor in the 1.38 μm region.

We found that modelocking the laser was impossible when we operated at a wavelength near the peak of the output power curve for the laser (1.45

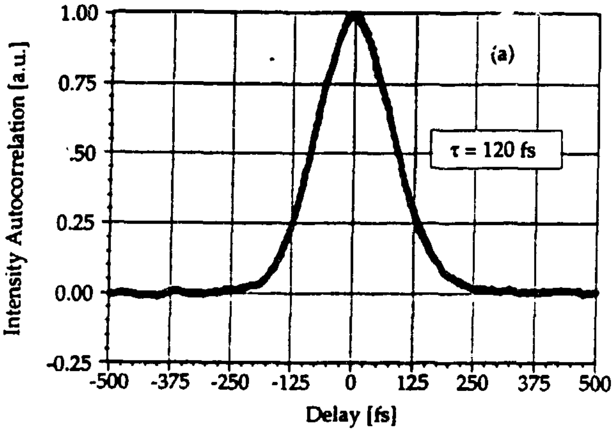

Figure 5: Autocorrelation of the modelocked output of the Cr:YAG mode-locked laser.

μm), which happens to coincide with the strong atmospheric absorption due to water. The absorption primarily introduces a strong dispersion into the cavity which cannot be compensated or overcome with bulk optics. This is the primary reason why the Cr:YAG laser has been impossible to modelock at the peak of it's tuning curve (near 1.45 μm). Inspection of the tuning curve shows that the water absorptions no longer exist above 1.5 μm. We installed fused silica prisms in the cavity, tuned the laser to operate at 1.53 μm so that we were operating above the water absorption band, and were then able to modelock the laser using regenerative modelocking. An autocorrelation trace of the femtosecond pulse is shown in Figure 5. A trace of the spectral content of the pulse is shown in Figure 6. The pulse is transform limited assuming a sech^2 shape.

To better control the pump profile in the crystal, we added a low power telescope in the pump beam, using two 5 cm focal length lenses separated by approximately 10 cm. By making small adjustments to the lens spacing, we were able to controllably change the curvature of the beam, which had a strong impact on the focal spot size in the crystal. A schematic of the laser cavity containing the small telescope in the pump beam is shown in Figure 7. After i erative optimization of the lens spacing and location, we were able to obtain self modelocking of the laser. The calculated beam profiles are shown below in Figure 8.

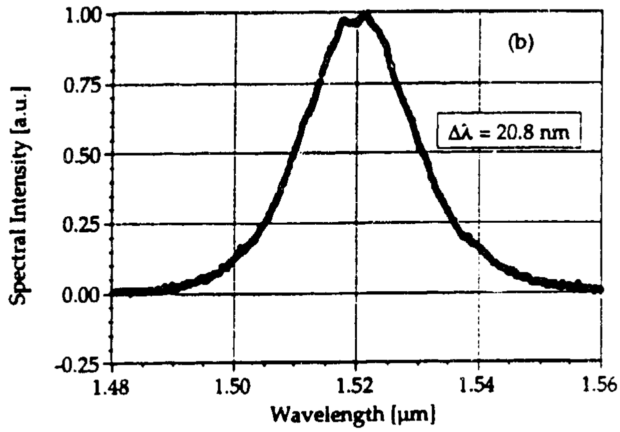

Figure 6: Spectral content of the modelocked Cr:YAG laser. The pulsed output of the laser is transform limited.

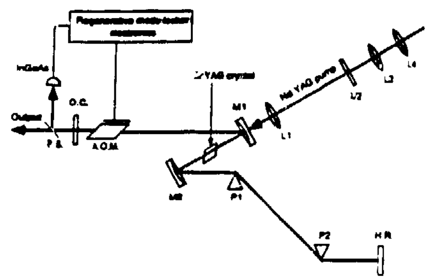

Figure 7: The calculated pump and laser beam radii as a function of distance from the edge of the Cr:YAG cystal, after the small telescope was added to the pump beam.

With this addition, we were able to self-modelock the Cr:YAG laser, and make it generate sub-picosecond pulses. We feel that careful mode control of the overlap between the pump beam and the laser mode was critical to obtaining self-modelocking from this laser. This result was published (A. Sennaroglu, C. R. Pollock, and H. Nathel, Opt. Lett. 19, 391 (1994)).

3 Thin Film Amplifier Research

Our work on thin film amplifiers did not come to a conclusion, but is still underway here at Cornell. We were able to deposit thin films of Cr:forsterite

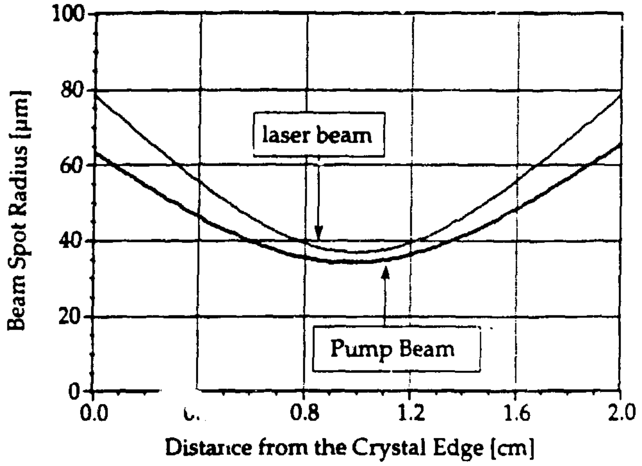

Figure 8: The calculated beam and pump radii in the crystal when the telescope was used to focus the pump beam.

on glass using a sol-gel deposition technique which involved spinning on the sol, baking it dry at 600 C, then spinning on another coat, etc. After ten coatings, the film was approximately 1 μm thick, but unfortunately it was heavily fractured due to residual stress caused by the difference in thermal expansion coefficients of the thin film material and the glass substrate. (We have recently also deposited approximately the same thickness film using e-beam ablation techniques, but again the films crack.) To counter this, we began exploring the use of nanocrystals imbedded in an index matching matrix made of polymer or glass. Forsterite particles approximately 100-200 nm in diameter were formed by sintering a sol under the proper pressure and temperature conditions. Powder samples were measured for absorption, emission, and emission lifetime, and were found to be consistent with bulk Cr:forsterite. We are now in the process of collaborating with a Material Science professor (Chris Ober) and a Chemistry professor (James Burlitch) on making the index matching matrix.

Because forsterite is a biaxial crystal, it will be impossible to perfectly index match it in an isotropic medium. Therefore, we can expect that there will be scattering losses associated with the randomly oriented particles in a index-matched host medium. The Rayliegh scattering due to these particles is given by

$$\frac{P_{scat}}{P_0} = \rho \frac{(n' - n)^2}{n^2} \frac{V^2}{\lambda^4} 24\pi^4$$

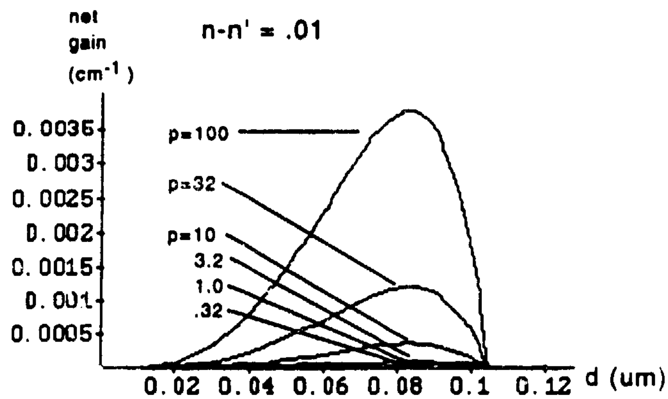

Figure 9: Estimated net gain from a solution of forsterite particles as a function of their particle size (horizontal a:) and density (p).

where ρ is the number of nanocrystals per unit volume, n' is the index of refraction of the scatterers, n is the index of refraction of the host material, V is the volume of a single scatterer, and λ is the wavelength of light. Making the particle size small reduces the loss due to scattering. Assuming a power gain as high as 50% per cm for forsterite, the trade-off between los and gain can be evaluated. Figure 9 summarizes one such calculation, showing the net gain expected as a function of the particle size. The term p repsresents he density of particles per cubic micron. Particles on the order of 100-200 nm are the optimum size for this system.

4 Conclusion

In this work, we were able to successfully modelock both the Cr:forsterite and Cr:YAG lasers using regenerative modelocking techniques. In the case of Cr:YAG, we were the first to succesfully modelock this laser in the sub-picosecond regime, and we were able to uncover the fundamental problem that inhibited modelocking of the laser. That problem was the excess dispersion caused by intracavity water absorption. We also discovered that self-modelocking was possible with this laser if careful control of the pump focusing optics was made. Proper beam overlap of the pump beam and the laser beam in the gain medium is critical to achieving self modelocking.

Finally, we began exploring the use of thin films of nano crystal composites for use as gain media in the near infrared region. We discovered some material problems in terms is creating a thin film which maintained optical integrity, and we began exploring the use of index-matched polymer hosts for use in thin film optical amplifiers.

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